Practical Localization of Passive RFID Tags

David Mazza

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Abstract. Many industries are choosing RFID technology for identification. RFID localization can be used for many applications, in virtually any environment where RFID tags are ubiquitous. This project explores the feasibility of localizing RFID tags. Distance is not directly measurable in an RFID system. This experiment introduces the idea that multiple qualitative readings can be compared to a fingerprint of the environment for trilateration calculations in order to localize a tag. This fingerprinting accounts for various tag orientations and takes advantage of various reader attenuations. Software was developed to create a fingerprint of any environment and to localize a tag. This RFID localization method is the first real method developed for localizing an RFID tag. Tags were successfully localized within two square feet. At most points, the localization was perfect, while at others, the predictions were negligibly inaccurate. The inaccuracies in the results were due primarily to RFID reader inconsistency, and mathematical imperfections. The RFID reader was studied very closely because it was used in a way that it was not intended to be. As a result, several unexpected findings were made during the course of this experiment. The next step in this project is to further study the fingerprinting and localization process. A unique probability comparison technique will be used, in place of the current comparison method. The results of the experiment show that RFID localization is feasible, and that we should see the concept utilized in applications where RFID technology is ubiquitous.

1. Introduction

RFID technology is becoming increasingly pervasive behind the scenes in many industries today. Even the public has had frequent exposure to the technology whether or not they realize it yet.

RFID tags are used in a wide array of applications today. An RFID tag today is excellent for storing unique, as well as generic information about its bearer. The name, UPC, description, and expiration date of a product can easily be stored on one RFID tag. By reading an RFID tag, all of this information can be retrieved instantly. RFID tags are only lacking in their ability to be localized. Although it can be read, it could not previously be found without prior or outside knowledge of its location. If there are 100 RFID-tagged products in a system, a database of the products can be generated easily, but that database is useless if the location of each product cannot be determined.

RFID technology today is used in many industries such as supply chain management. RFID tags are enormously useful for inventory. A system can keep track of its contents at any given moment, and when an item is removed or placed into the system, that item will immediately be accounted for in the inventory. This is the concept of a Smart Shelf.[11]

RFID localization is naturally the next frontier in RFID technology. There are a few localization concepts in existence, [7, 12, 13] however; I consider these to be “pseudo-localization.” There is no other project that aims to localize a tag using nothing other than an RFID reader, and a tag. LANDMARC uses RFID as reference tags [12], another only mentions localization of tags through a similar, simplistic technique. [5] Ferret [7] comes closest to real localization, but it uses camera in addition to an RFID system and it still cannot truly find the distance that the tag is from the reader.

2. Principles of Localization

Localization is generally defined as the determination of the location of an object. In robotics, "localization" is a reference to a robot determining its own location in a closed system consisting of other robots or landmarks. [1] Through the course of research, I sought to do the opposite; there may be many passive tags in any given system; it was my objective to localize each of these with respect to the RFID reader using a method called "trilateration".

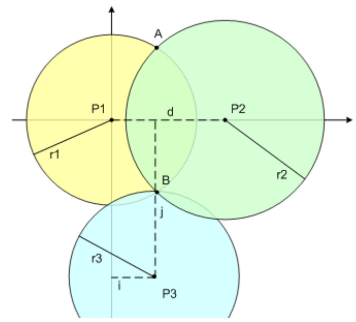
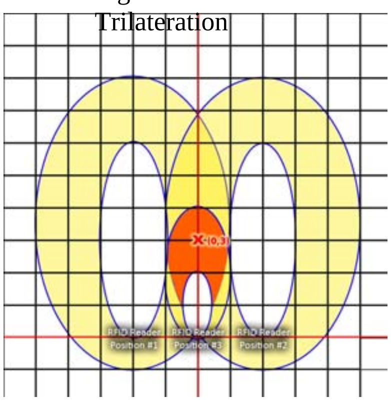


Figure 2.1 Traditional Trilateration

2.1 Trilateration

Trilateration is most commonly used in radar systems and the detection of seismic activity (earthquake localization). Trilateration is similar to the more common localization method of "triangulation". The terms are sometimes used interchangeably, however, in this case, they are not; there is an important difference between the two methods. Triangulation is based on the measurement of angles, where trilateration is based on the measurement of distance. [2] While this system has the ability to measure angles, this is only incidental and occurs after trilateration has been completed, making it useless for triangulation. Triangulation can be used to verify trilateration measurements, but such checks constitute an ineffective use of time and energy.

Figure 2.2 Modified Trilateration


This concept is based on the estimation of distance (r) of a tag from the reader at any given angle (θ). Therefore, trilateration is the optimal method of localization using the data that was collected. There is, however, one important difference between traditional trilateration and the trilateration used here. [Figs. 2.1 and 2.2] Consider a seismic activity detection system; a seismometer is indifferent to angle or direction (omnidirectional). If a seismometer determines that an earthquake is 1000 kilometers away the earthquake may have occurred anywhere on the circumference of a circle with a 1000 kilometer radius. An RFID reader, by contrast, is neither omnidirectional nor indifferent to angle or direction. An RFID reader's optimal range is line of sight. It has the ability to read a tag peripherally or directly behind itself, but the probability of successful feedback is considerably smaller (this concept is highly complex and requires detailed explanation to be provided in Section six). Therefore, if all the possible locations of a tag were to be mapped out based on a reading, it would form an ellipse. Points in front of the reader must sit at a much greater distance, while points situated peripherally must sit closer the reader. If the tag were detected behind the reader, it would be no more than two or three feet away. [Fig. 2.2] The elliptical shape formed by the trilateration employed here underscores the cardinal difference between it and traditional trilateration.

2.2 Planar Localization

Localization can occur in either two or three dimensions. Trilateration can be utilized in three dimensions by intersecting spheres rather than circles. [3] For the sake of time, the feasibility of RFID localization was tested only on a two-dimensional plane. Imagine, if you will, antennas and tags, level on this two-dimensional plane that runs parallel to the ground; this effectively eliminates height as a variable, and greatly simplifies the entire process. Although a real-world application would require the use of a *three-dimensional* trilateration, two dimensions were sufficient for this experiment (I will elaborate further on this assertion later in the paper).

2.3 Pre-existing Data

The final and by far most integral aspect of this localization method was the collection of certain "pre-existing" data. This was the most time consuming aspect of my research, which, in and of itself, became the single most significant limiting factor. Of course, no data can actually be pre-existing. I will elaborate on the collection of this data, also known as the fingerprinting process, in section 4.

3. Localization Concept

Before explaining the RFID fingerprinting procedure, it is important to understand why it was so important, and appreciate the means to the end goal. This section will summarize the overall concept of localizing a tag. However, you must realize as you read this section that it is written with the assumption that the "pre-existing data" has already been gathered.

3.1 Finding an RFID Tag

To actually localize a tag, the first step is to find the tag(s) in the system (room) with the RFID reader. To "find the tag(s)" does not simply mean to find a tag, and then ignore it. Rather, it means to actively scan the room for tags, and attempt to find every tag, in every attempt. Only one tag was used to eliminate other variables in the experiment. The process of finding a tag is as such: [Fig 3.1]

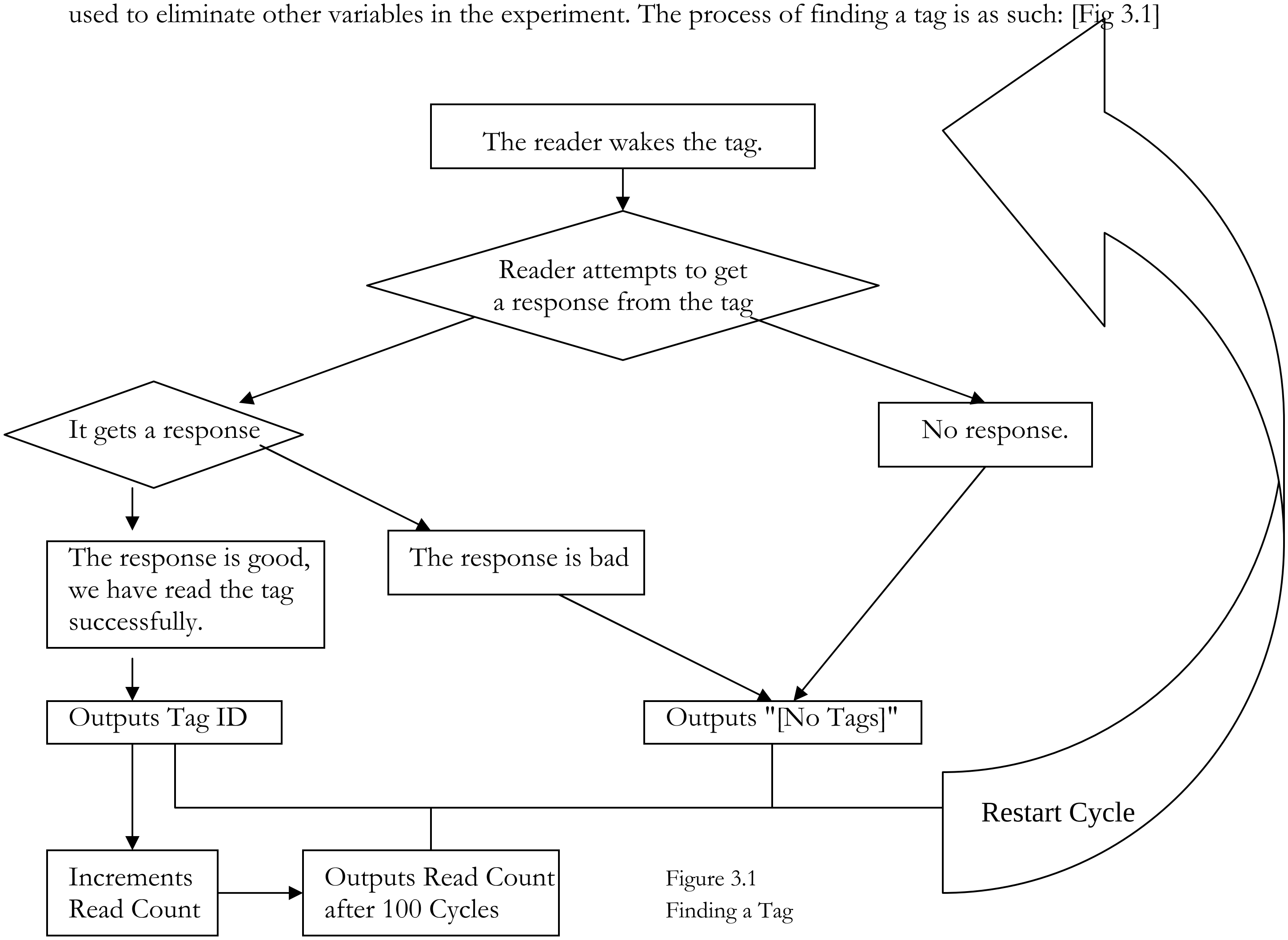


Figure 3.1
Finding a Tag

I will go in depth on how we use that information in the next section, but for now, I will leave it at that. It is only important for now to understand this entire process as one cycle. Several of those cycles combined are referred to as a "reading" which is simply a number that is calculated from the results of the cycles.

3.2 Summary of the Process of Localizing a Tag

Once the reading has been taken, it is compared to the readings of pre-existing data. Now most points in the room can be eliminated as possible locations of the tag. The aim is to create a list of possible locations of the tag. The antennas are moved and another reading is taken. Again, even more points can be eliminated. A few more readings may be taken following the same process, until enough points have been eliminated to produce a result that is deemed to be accurate. At this point, there is a general idea of where the tag is located in the system. The result will be checked against the actual known location of the tag, and percent error will be calculated. With this simple method, the location of the tag can be estimated with great accuracy of about 90 - 100%. At certain points, 100% accuracy is achieved. However, this is mostly due to the granularity of the possible locations.

Although this experiment has produced seemingly accurate results, the accuracy of these results must be put into perspective, before reaching a conclusion. It is true that at certain points in the room, 100% accuracy can be acheived , but why does it only work that way with certain points, and what is meant by "100% accuracy"? The most important aspect that is artificially improving the results is the granularity that was chosen. For the fingerprinting, readings were taken at points on a grid with two square foot cells. This means that any prediction is only accurate within two feet.

3.3 Granularity

Granularity is generally defined as the extent to which a larger entity is subdivided. [4] Granularity as it is used here is the distance between the chosen points at which readings were taken. A granularity of 2 square feet was chosen for this experiment; however, there is no reason that this couldn't be changed to fit any scenario. This granularity was chosen for convenience and time.

4. RFID Fingerprinting

The majority of work for this research project was taking readings at more than 85 points in a room. This part of the project leads to innovation, and discoveries that were never expected. Dr. Himanshu Gupta and Dr. Samir Das were consulted about the best way to go about this. They have been a part of several other RFID research projects, so they have a great deal of experience with the reader. The advantages of automating the readings were discussed. Ultimately, I developed a method of automating the readings, which will be discussed in sections 4.4 - 4.6. The RFID fingerprinting took almost two weeks to complete.

4.1 Tag Orientation

The WINGS Lab at Stony Brook University studied the effects of tag orientation. [5] Preliminary experiments were performed to determine the effect of tag orientation on the readings. The goal for these experiments was to determine if the effects were significant enough to make a difference and to determine which simple orientations caused the readings to differ the most. Due to the time limitations, only a few tag orientations could be chosen for the fingerprinting. The plan was to choose about four or five orientations for the fingerprinting. This alone would mean that over 400 readings would need to be taken. Since each reading takes about 2 minutes, that meant about 14 hours of readings.

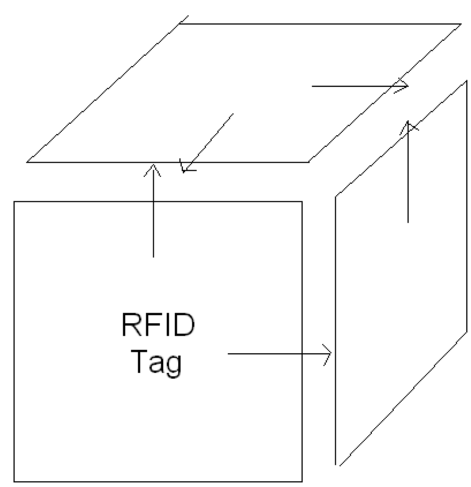


Figure 4.1 Tag Orientations

Upon completion of this preliminary experiment, five tag orientations were chosen. [Fig. 4.1]

4.2 Reader Attenuation

Attenuation can be generally defined as the decrease in intensity of a signal, or beam.[6] By increasing attenuation the range of the reader is decreased. A fingerprinting was taken for a few different attenuations and this data was used for localization as well. Attenuation can be one of the most useful tools for RFID localization. Ferret [7] mentions attenuation as a simple future endeavor for their project, however, this oversight may have been larger than they conveyed it to be.

Although attenuation can be very useful, it is not as solid as one might expect it to be in an RFID application. One would expect the concept to be very simple. For example, if 0 attenuation can read up to 30 feet, 50 attenuation can read up to 25 feet, and 100 attenuation can read up to 20 feet, then distance calculations can easily be based on differences between attenuation fingerprintings. If a tag can be read at 0 and 50 attenuation, but is lost at 100 attenuation, then the tag must be 20 - 25 feet away. However, attenuation is almost never quite that solid, or reliable. I will discuss percent error and consistency later.

Ferret seems to make the assumption that attenuation is just as simple as the example given above. Furthermore, it was clear from their paper that distance measurement was not one of their main focuses. This is why I consider my research to be the first look into "true RFID localization".

Even though attenuation is not as simple as others make it seem, it was not discounted in this experiment. This experiment takes a different approach by doing three different attenuation fingerprintings; zero attenuation, medium attenuation, and maximum attenuation.

4.3 Granularity

Before the fingerprinting began, several things were taken into consideration, while always keeping in mind the time budget. The most important factor was granularity, which was only limited by time. Ideally, one would like to take readings at thousands of random points in the room to get a true fingerprinting. However, I did not have a robotic system to move the tag for me, so I had to physically be present for every reading.

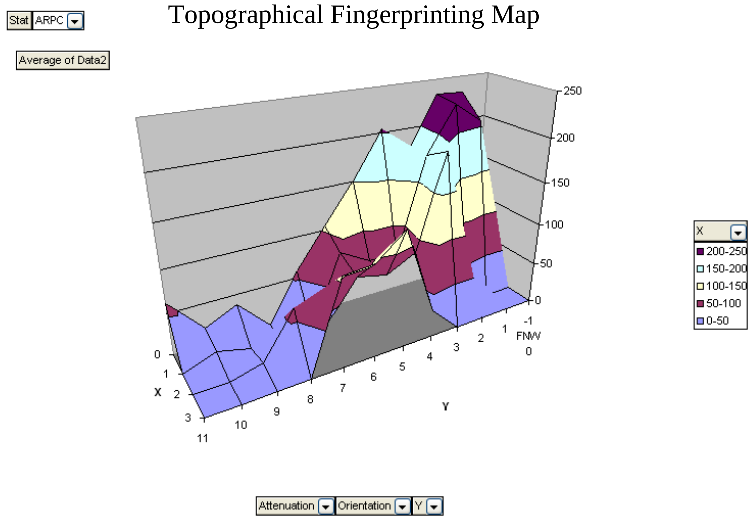
A systematically simple and accurate system was devised for the fingerprinting. In the large room that the fingerprinting was performed in, there were two square foot ceiling tiles. This made an excellent Cartesian coordinate system, and very simple math. Readings were taken with the tag directly under each ceiling tile intersection. There were about 85 points in the room that were within the reader's range at this granularity.

4.4 Automation

With a time budget, efficiency was integral to the success of this experiment. I had to devise a way to take the readings as efficiently as possible, without wasting too much time to create that system. I was given a week to devise a system, as well as for my preliminary experiments (explained above). Ideally, one would want to create a robotic system to move the tag, and let it go for a few weeks. However, obviously such a system would be very expensive, and far too complex.

While I concluded with my professor that I would need to be present for all the readings, we did debate over whether or not to automate the readings themselves. "Automation" as it is used here is the instantaneous logging of readings and generation of statistics by a computer, rather than a human using the included software. I started initial

Figure 4.2
Topographical Fingerprinting Map



experiments by taking readings manually.

Dr. Gupta contested that manual readings were good enough for this experiment. He also made a valid point by saying that designing a program for automation might be too difficult, and time consuming.

The process of a "manual" reading is as such:

1. The reader searches for tags.
2. The reader's included desktop software is used to display the read count in real time.
3. An estimate of the average read count is recorded.

Clearly this is a very inaccurate method. It is also very inefficient. The reader tends to produce somewhat inconsistent results, especially when it is observed in real time. There seems to be almost no consistency at all. This is largely due to the fact that the RFID tag has little to no power over the radio waves. It can do no more then reflect them. The RFID tag cannot filter out poor radio waves, and therefore, instantaneous manual readings seem obscure.

An "automated" reading is much more accurate and efficient. In an automated reading, every read count for each cycle is recorded in a database, and from that database, statistics can be calculated. There are several advantages to automation. [Fig 4.3]

- In a real world scenario, the readings would obviously be automated. By automating the readings early on in the project, we are that much closer to the real product.
- All the estimation and guessing of manual readings is eliminated with automation. The exact average read count can be calculated, rather than estimating it from real time results.
- With automation, a set number of cycles are performed in each reading. Unlike a manual reading, where the number of cycles could vary.
- With automation, we can even calculate other useful statistics that would not be attainable manually; including:
    - Average
    - Median
    - Percent Error
    - Maximum read count
    - Average time per cycle
    - Total Time

Figure 4.3
Advantages of Automation

Clearly, automation is the best method. However, it's not the easiest. Automation can mean almost anything. In this case, the only process that was automated was recording the readings. This is not a simple task by any means. Firstly, automation keeps the amount of read attempts constant, from which a percent error can be calculated. At each point and scenario, a constant amount of attempts to read the tag are made automatically. Secondly, there is no estimation or possibility of incorrect data entry. Each calculated statistic is automatically recorded in a master database.

4.5 Further Automation

Not everything is automated. There was no robotics involved in my research, although it would have been very useful. This was a limiting factor to this experiment. A certain granularity was agreed upon for the sake of time.

With a robotics system to move and reorient the tag, readings could be more consistent and accurate. Readings could be taken at random points in the room, which would be measured against a laser, ultrasound, or cricket mote system. [8] This would generate a true fingerprinting. I would recommend such a robotic system for future research with a larger budget.

With the robotic system described above, one could also perform the fingerprinting in a three-dimensional system. This would ultimately be necessary for an end product. Eliminating the need for a human in the fingerprinting would greatly expand the potential for this research.

4.6 My Automation Work

The Alien 9800 RFID Reader included an application programming interface (API) with documentation and code samples. While the reader was not built for our purposes, I was still able to work with it through its superior API.

I starting writing my software based on their very simple code that simply connected to the reader and made one attempt to read the tag. I built my application in Microsoft Visual C#. [Fig 4.4] The figure on the next page shows the final application, which took the fingerprinting, calculated and

Figure 4.4 Automation Software

logged stats, and even localized the tags.

5. Localization Based on Completed Fingerprinting:

Earlier in section 2, the principles of localization were discussed to make the concept clear. In section 3 the concept itself was discussed. In the previous section the fingerprinting was discussed. This will now be referred to as "pre-existing data" again. This section will reveal how it all comes together to actually localize an RFID tag.

5.1 Basic Localization Process

As you know, trilateration was used to localize the tag at its unknown location. Here is the overall process that was developed to locate a tag:

1. Take a reading of the tag at its unknown location. [See section 3.1]

2. Generate Statistics from the reading. [See section 4.4]

3. Compare the statistics to the database of readings at known locations (pre-existing data). [See section 3.2]

4. Eliminate all the points at which we are now confident the tag is not located. [See section 3.2] For example: if I know that the tag is close to me, then I will eliminate all points that are far away.

5. Continue moving, and repeating steps 1-4 until enough points have been eliminated to leave a small enough prediction of the tag location to be considered accurate.

-A gyro could be used to detect motion of the end user, and relate the user's current position to his position at the original reading. This would create an artificial and temporary "global coordinate system" until the tag is reached.

That is an example of a process for the end product. However, the goal was not to create an end product, but rather to research the feasibility of one. For this reason a three dimensional fingerprinting or small/zero granularity was not needed. The above process can be as complex or as simple as it needs to be.

A gyro was not used at any time during this experiment. Instead, the reader was only moved to certain fixed positions. This created the same simple artificial global coordinate system.

5.2 Results

The results of the localization based on the RFID Fingerprinting were impressive, and *promising* for the future of RFID Localization. With the large granularity used, tags were located with 90% - 100% accuracy, which was much greater than expected. This clearly indicates that the difficulties of obtaining a "pseudo-distance measurement" can be conquered to produce a reasonably accurate estimate of the location of an RFID tag.

6. RFID Localization Based on more Advanced Fingerprinting and Statistical Techniques, for "Real-World" and "Zero Granularity" Settings

While the only goal of this research was to determine the feasibility of RFID Localization, the project will continue. We plan to take my concept to a new level by using a complex statistical technique for the fingerprinting. This would virtually eliminate granularity, and would be much closer to an end product.

In an ideal world, a model would be developed to determine the position of a tag in any given environment. However, due to certain unique behaviors of the reader, this simply would not be feasible. Instead, calculating the probability of a tag being at any given location in any given environment would be the best route to take.

6.1 A Unique Statistical Approach

We consulted with a Ph.D. candidate in electrical engineering, Mahesh Vemula, who is basing his thesis on a technique where (from my simplistic understanding) you can calculate the probability of a probability. For example, let us imagine that Rob the RFID enthusiast and hunter is hunting birds. There is a certain probability that Rob will be able to kill a bird with in certain number of tries (let's say 10), and that probability is largely dependant on the size of the bird, and the distance it is away from him. If the bird is sitting right in front of him, Rob can almost count on being able to kill that bird 100% of the time. If the bird is a fair size, and a fair distance away from him, then perhaps Rob can almost count on killing it 50% of the time. If the bird is a mile away, and quite small, Rob would almost expect never to kill it. However, you might have noticed that in all three scenarios, the word "almost" is used. Rob might miss the bird sitting right in front of him once in a while, however unlikely. Rob might vary significantly from the 50% shot. If Rob is lucky, he might hit the small bird a mile away once in a while.

We cannot count on the average probability, but rather the probability of obtaining any given probability. This will tell us the how strong our prediction of the tag's location is, and may also give us more clues as to its location. If we know that at a certain range, the probability varies significantly, then with only a few tests, we can find out how much those tests varied, and be able to calculate again, the probability of the tag being located at any given place. We can actually find the standard deviation of a probability at any given point, and graph it to a bell curve, and then use these bell curves in our prediction. This is the point where our PhD candidate's paper would take over to explain the rest, but the exact method is not crucial to my point. This may sound somewhat circuitous, but we found the reader's behavior can vary somewhat significantly. We are looking into the issue, but we still feel that this technique would be a strong addition to my localization technique.

To better explain the benefits of this technique, suppose any result could be obtained at any point in any scenario. Looking back at the hunting example, what if Rob could shoot with 100% accuracy from a mile away, and 0% accuracy from 2 feet away. That is very unlikely to happen, but let us suppose that it could. We would still assume that the opposite is expected at the respective points. So perhaps 1 mile favors 0% accuracy 99% of the time, and 2 feet favors 100% accuracy 99% of the time. We have a similar case with the RFID tags. Certain points favor certain results (as would be expected). While we know what to expect at any given point, it is great to be able to calculate how strongly we can expect that result.

6.2 A More Realistic "Zero Granularity" Fingerprinting

Now that this new probability technique has been discussed, the plan for the next more advanced fingerprinting must be discussed. I actually started an experiment by rebuilding my automation program to automatically take a series of readings every half hour over night with the tag at one point. We could take these readings, and if we moved forward with this method, we could have drawn a bell curve based on every reading. To continue this, we would simply move the tag to a new location every night.

Zero granularity is an amazing concept that we are now confident we can attain through this method. We can take these over-night readings at random places in the room, (using something like a cricket mote or laser to measure the real location) and calculate the bell curve for each location. If we can compare these bell curves between locations, then apparently we can almost instantly generate a bell curve for literally any point in the room on demand. This would create a completely zero granularity scenario where there are no holes in the fingerprint. One could compare this concept to vector graphics [9] as opposed to raster graphics. [10]

6.3 Looking Ahead

Since we are calculating the probability of a probability, we can take readings in different environments, and actually strengthen our fingerprint. At this point we would be coming very close to a final product that would be usable in the real world, where we would be faced with a multitude of various environments, and obstacles.

My role in the next step of the project will be to develop the automation software to take nightly readings. A graduate student will continue the fingerprintings and Dr. Himanshu Gupta and Dr. Samir Das will continue to work with the PhD candidate on the statistics aspect.

7. Unexpected Findings

Unexpected outcomes are often the most exciting and insightful. This project was no exception. One of the most interesting aspects of my research was the unexpected findings. By the tedious nature of the fingerprinting, I was simultaneously studying the behavior of the reader in a way that no one else ever has.

7.1 Early Mistakes / Discoveries

Unfortunately I did encounter a few unexpected findings at the beginning due to a lack of proper instruction and documentation which was found soon after. At first I was not aware that the reader was bi-directional. (where there is a separate transmitting and receiving antenna) Luckily, this lack of knowledge did not have a detrimental effect on my work up to that point, and I did learn a lot about the reader within that time. I was able to proceed without much delay, by taking a second fingerprinting.

One of the earliest unexpected discoveries that I made was the effect of walls on the performance of the reader. Walls actually seemed to artificially increase the amount of times that the tag was read. As the tag's distance from a wall decreased, the readings increased (in a scenario where without the wall, the inverse would be expected). My hypothesis is that the wall actually caused a bounce back effect, which effectively woke the tag more rapidly than intended, and allowed the reader to read the tag more frequently (artificially increased the probability that the tag would be read).

I was originally given a paper from the WINGS Lab which had worked with the reader before with details about the reader's range. I based my original fingerprintings on this paper, only to find out later that the range was much greater. This mistake was probably made due to dead spots at certain ranges.

7.2 Dead Spots

Quite possibly the most significant unexpected finding that I made was about the dead spots within the reader's range. It took me several weeks to fully realize what was actually going on. I discovered that the reader could not read a tag that was about 12-14 feet in front of it, or 20-24 feet in front of it. At first I had only known about the 12-14 foot dead-spot, because I thought that beyond 20 feet was out of range. We came up with a hypothesis that there may have been a discontinuity between the omnidirectional (incidental) range of the reader, and the directional range. However, upon discovery of the farther dead spot, this hypothesis does not seem as likely, unless the dead spots are unrelated. We are still looking into the issue, and have made attempts to reach the manufacturer of the reader.

7.3 Change in results over time

The second most significant unexpected finding in this project was the change in results in a time-span of only a few hours. I found my results to be inflated at the beginning of the day (or deflated at the end of the day). During the fingerprinting, I would start at 8 am, take constant readings, go to lunch at 12, and when I would come back, I found the results to be a bit higher than when I left. At some point, I decided to test the point (0, 3) every day at various times. I was shocked to find that the results varied fairly greatly. It seemed to me that the reader would become progressively "lazier" as the day went on. Consistent use actually produced lower numbers over time. I had no grand hypothesis for the cause of this problem, nor did my professors, but I did come up with two ideas to get around this. I decided to take constant unrecorded readings for an hour or two every morning to "warm up" the reader. Then I would record readings once I felt that the reader was giving a low enough value for (0, 3). I also thought that it was the consistent consecutive readings causing this. I tried taking automated readings every half hour for 24 hours.

8. Conclusion

Practical RFID localization does not seem far off. Pseudo-localization techniques currently exist for RFID tags due to the demand. "We have no doubt that this standard will encourage widespread adoption of wireless location systems as the technology has already been proven to deliver tremendous bottom line cost savings for enterprises around the world," said Larry Graham in reference to a new software standard passed for current "pseudo-localization" techniques.

In conclusion, real practical RFID localization is not only feasible, but accurate, and with plenty of room for improvement. With the use of this modified trilateration concept, an RFID tag can be located based on any type of fingerprinting. Automating the process was an integral element to the success of this experiment. The powerful API enabled this type of automation.

There is plenty of room for improvement upon this experiment. The most glaring limitation to this experiment was the use of a reader to perform a task that it was not designed to perform. If a reader was built more specifically for this purpose, the results would improve significantly.

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